

A Holistic Approach to Guide Development of Future Climate Scenarios for Water Resource Applications

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Abstract: Changes in climate are expected to have a substantial impact on water resources. Consequently, numerous hydrologists have studied the widely recognized challenge of using climate-change projections to address questions related to management of future water resources. Significant effort has been invested in formulating methods to overcome the difference in spatial scales between available future climate scenarios and water management needs. While numerous downscaling options exist, resource evaluation for the various approaches is rarely discussed; most assessments are focused on evaluating the skill of different methodologies. In this study, a framework is described that water managers can use 1) to identify their climate scenario needs and 2) to assess their financial, computing, time, and workforce resource limitations for climate scenario development. This framework will enable water resource managers to optimize the use of their available resources when developing future climate scenarios.

Keywords: *Downscaling, climate scenarios, water resources*

Water resource managers in governmental agencies and other organizations are increasingly focused on preparation of climate-related vulnerability, adaptation, and mitigation assessments. These climate-related assessments require information on future climate, particularly possible changes to precipitation and temperature. To meet this need for future climate information, many managers will look to global climate models (GCMs) as a primary data source. Yet, a major limiting factor has been the resolution mismatch between coarse predictions from present-day GCMs and what is often needed for hydrologic applications and water resource management.

The scale mismatch between GCMs and water manager needs has been the focus of extensive discussion in the scientific literature (e.g., Varis et al. 2004; Diaz-Nieto and Wilby 2005; Wilby and Harris 2006; Buytaert et al. 2010). Numerous downscaling techniques (e.g., spatial and temporal analogues, statistical downscaling, regional climate models) are available to address this scale mismatch, with the techniques varying in terms of

their skill, complexity, and computational demand (e.g., Mearns et al. 2003; Wilby et al. 2004). Many guidance documents have been prepared to address the scientific aspects of downscaling (Mearns et al. 2003; Lu 2006; Carter 2007; Lu 2007; Knutti et al. 2010). Less attention has been paid to understanding how non-scientific constraints to climate scenario development impact downscaling technique selection. This issue was highlighted in a recent United Nations Development Programme guidebook (Puma and Gold 2011), which argues that financial, computing, time, and workforce constraints should be considered jointly with scientific limitations in order to develop climate scenarios that meet end-user needs.

Water resource managers need a holistic framework that allows them to recognize and account for the interconnectedness of scientific and non-scientific constraints associated with climate scenario development. Building on the work of Puma and Gold (2011), this study introduces a holistic framework to guide water resource managers through the process of climate scenario development. This framework will assist these

managers as they work to balance their agency's available resources with their climate scenario needs and scientific downscaling constraints.

Evaluate and Determine Needs

To deal with the complexity of climate scenario development, water resource managers first need to evaluate and determine their climate scenario needs. Before initiating this evaluation process, water resource managers should consider the formation of an interdisciplinary team to plan and execute climate scenario development (Puma and Gold 2011). Ideally, team members would include a climate scientist, a hydrologist, and an expert

on water policy and management. Depending on the climate scenario end users, agricultural experts and engineers might also be involved. Once team members are identified, the team can begin to determine its needs and organize its work within the context of water resource management.

Figure 1 presents key questions that the interdisciplinary team should address to determine the purpose and needs for climate scenario development. The question on end-user identification can help the team develop climate scenarios with relevant information. For example, water resource managers are typically concerned with flooding and droughts, which necessarily requires information on extreme precipitation

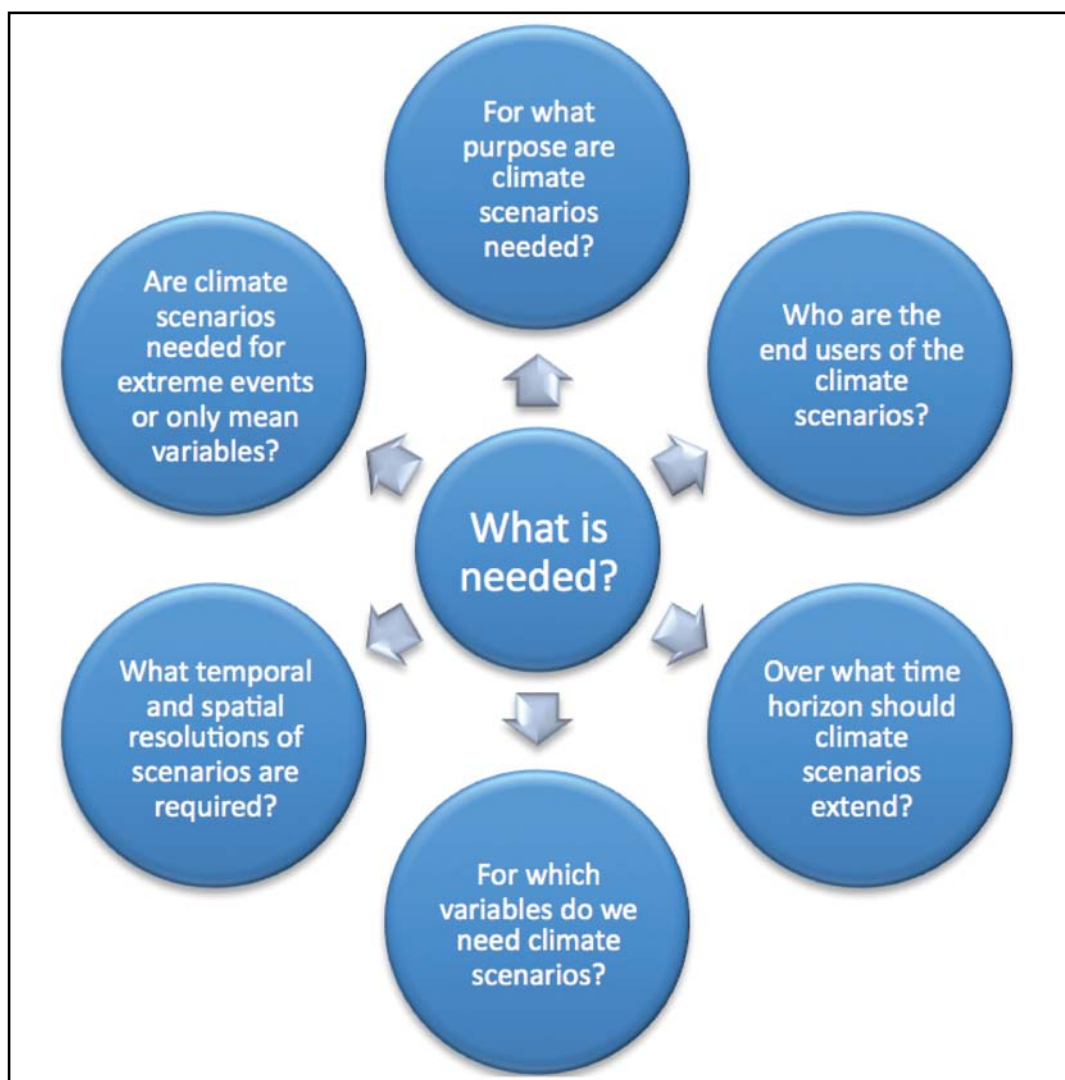


Figure 1. Key questions to determine the purpose and needs for climate scenarios development. Adapted from Figure 5 (Lu 2006).

events. These precipitation data can then be used for the design, operation, and maintenance of infrastructure (including levees, dams, and sewers). Conversely, if the end user is an agricultural manager, data on statistics of daily precipitation and temperature (e.g., frequency, intensity, and duration of droughts) during the growing season is essential. Clearly, understanding end-user needs can streamline climate scenario development and render it more efficient and cost-effective.

As part of the evaluation process, Figure 1 clarifies that water resource managers must select the time periods (e.g., 2030s, 2070s, 2100s) of the climate scenarios. Time-period selection will largely depend on regional development plans, including cost-benefit analyses of infrastructure projects. The time resolution (e.g., daily versus monthly precipitation) of the climate scenarios will also depend on end-user needs (i.e., farmers needs are different than reservoir-operator needs). Time resolution will ultimately influence the downscaling approach selected, because prediction skill of downscaling methods is highly dependent on the target variable (e.g., monthly temperature or daily minimum, maximum, and mean temperatures). For spatial resolution, water resource managers must assess a number of main factors: (1) size of region; (2) physical geography, including a region's land cover (forests, crop, urban, etc.), topography, proximity to the ocean and surrounding mountains, and watershed characteristics; (3) large-scale climate patterns (e.g., El Niño-Southern Oscillation); and (4) target application (Puma and Gold 2011). Generally, end users would prefer climate information at the highest possible spatial and temporal resolutions available. However, the team of experts should identify the resolution that minimizes the need for non-scientific (financial, computational, time, and workforce) resources and is sufficient to be useful to the target water resource project. These non-scientific resource constraints will be discussed further in the next section.

Identify Existing Resources

With the climate scenario needs from the preceding analyses, a feasibility assessment is the next step for water resource managers and their teams of experts. Fundamental questions that the

teams should address as part of this feasibility assessment are presented in Figure 2. These questions highlight basic issues of data availability, model skill, and other constraints. Questions in Figure 2 will require substantial consideration by water resource managers and are discussed further below.

Observed climate data for a region is critical to climate scenario development and the extent and quality of these data will often limit the range of downscaling options available to water resource managers. Many of these managers will already have detailed observational climate data for their regions. If not, analyses of existing meteorological data (temperature, precipitation, wind, etc.) should be initiated immediately. Even if observation data is available, data quality will be an issue for many regions. Managers should therefore consider evaluation of the number of stations, areal coverage of the data, length, and quality of the records (Feng et al. 2004; Teegavarapu and Chandramouli 2005; You et al. 2007). Quality control of observational data is typically a time-consuming process; water resource managers should be aware of and plan for this. If, as with many developing countries, the regions are data-poor, then project managers may consider compiling data sets from other sources to approximate the region's climatology (e.g., New et al. 2002; Hijmans et al. 2005; Sheffield et al., 2006; Kamiguchi et al. 2010).

The question in Figure 2 on non-scientific constraints to climate scenario development can be understood through Figure 3. This figure schematically presents the relationship among analysis complexity, spatio-temporal resolution, and non-scientific constraints to climate scenario development. "Complexity of analyses" in Figure 3 refers to the extent of the approach. For example, an approach with relatively low complexity would be an analysis where climate scenarios are obtained with a single GCM for one realization only (i.e., not accounting for uncertainty due to internal climate variability). Conversely, an analysis with high complexity would involve output from many GCMs with multiple realizations for each GCM, where several downscaling techniques are employed. With regard to spatio-temporal resolution in Figure 3, a low-resolution case would have scenarios with a similar resolution to

GCM output (i.e., monthly output for $2^\circ \times 2^\circ$ grid cells), and a very high-resolution case might have climate scenarios at a daily, 1-km resolution.

Figure 3 illustrates qualitatively that complexity of analyses and spatiotemporal resolution will depend on a project's non-scientific (financial, computing, time, or workforce) constraints. As non-scientific constraints increase, the possible complexity and resolution of climate analyses will generally diminish. Three hypothetical examples are highlighted in Figure 3: (1) no constraints; (2) medium constraints; and (3) significant constraints. The three constraints are paired with an appropriate climate scenario-development method that matches the constraint level presented in each case. This figure demonstrates the interplay

between non-scientific constraints and the choice of spatio-temporal resolution, as well as the complexity of the decision-making and analyses processes. Water resource managers can use Figure 3 to guide discussions with their team of experts when discussing possible options for climate scenario development.

Holistic Framework for Climate Scenario Development

Figure 4 links together the issues discussed in previous sections in a framework that is intended to guide water resource managers through the climate scenario development process. This framework, together with Figures 1 to 3, can help

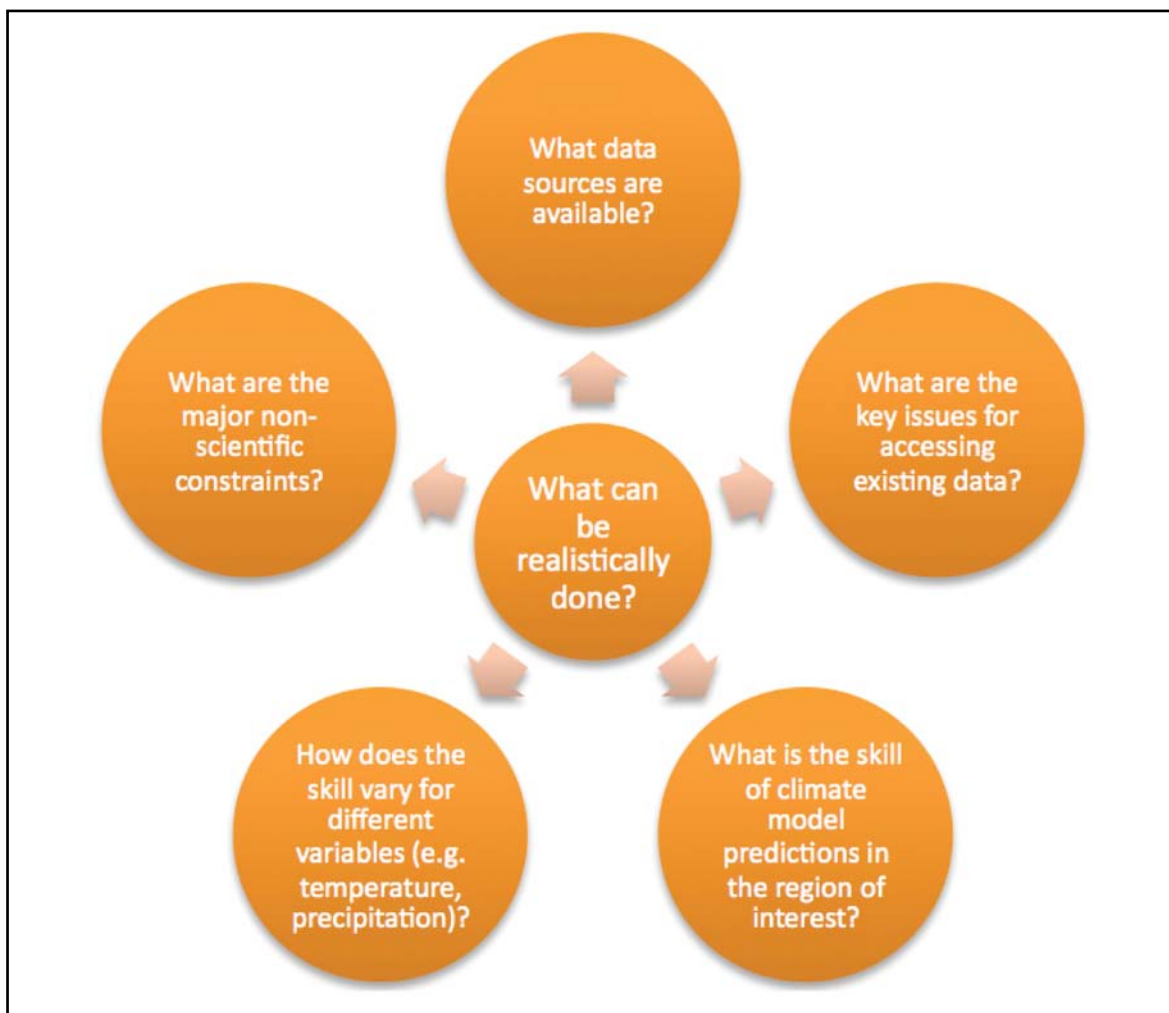


Figure 2. Key questions to assess what can realistically be done when developing climate scenarios. Adapted from Figure 5 (Lu 2006).

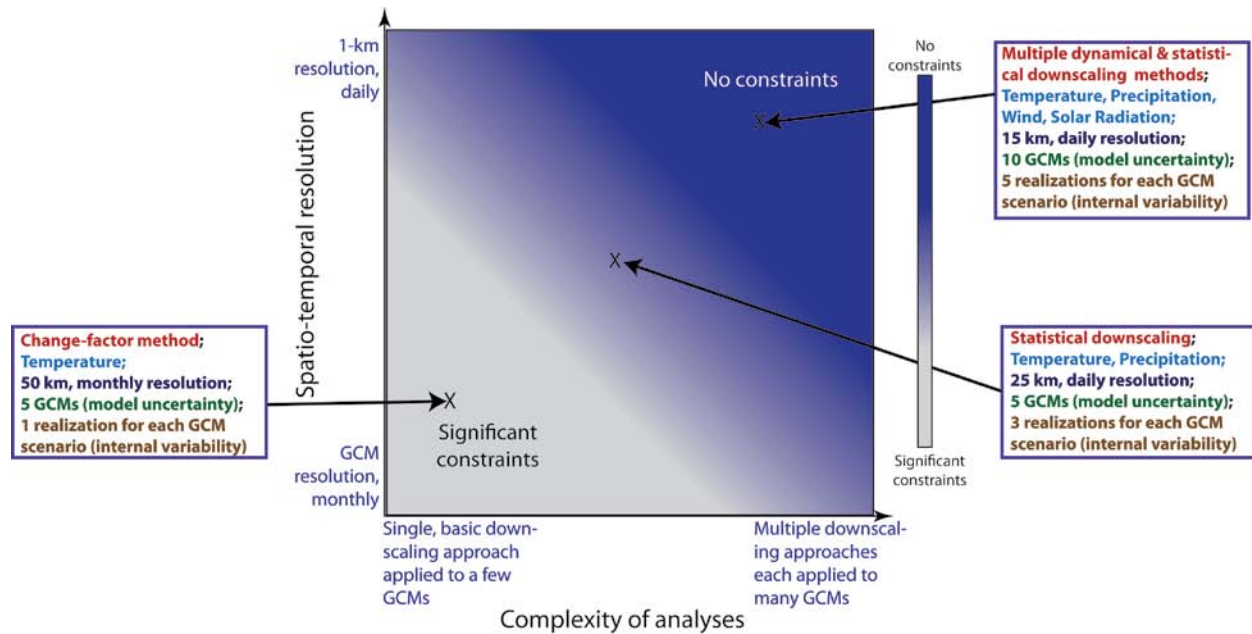


Figure 3. Interplay among non-scientific (financial, computing, time, or workforce) constraints, complexity of analyses, and spatiotemporal resolution for climate scenario development.

these managers identify the reasons driving their scenario development, recognize project constraints, and understand the interplay among these constraints to better approach climate scenario development. Additionally, the uncertainty associated with climate scenarios is key information, especially for scenario end users. Communicating information on uncertainties will allow end users to develop more robust climate information for their water-related studies and management plans.

The framework explicitly recommends that water resource managers consider uncertainty in greenhouse gases (GHGs) by choosing bounding emissions scenarios. An alternative would be to select a ‘middle-of-the-road’ scenario, but it is unclear whether such a scenario could be realistically identified. The most accessible scenarios on GHG emissions are from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000). These scenarios were used in the IPCC Fourth Assessment Report (AR4) analyses. While the SRES scenarios are currently the most widely used emissions scenarios, efforts are underway to replace these scenarios. If water resource

managers are using AR4 climate model data, then they may build their range by considering, for example, the SRES A2 and B1 scenarios. These scenarios correspond to a range of approximately 540 to 970 parts per million of carbon dioxide in the atmosphere in 2100 (IPCC 2001).

A new approach to deal with uncertainty in GHG emissions, termed Representative Concentration Pathways (RCPs), was introduced as part of the IPCC Fifth Assessment Report (AR5). For further discussions on RCPs, readers are referred to Moss et al. (2010). It is possible that RCPs — although not forecasts or boundaries for potential emissions — may be used to develop a prospective range of climate scenarios, because they represent the radiative-forcing range in the scientific literature (at the time of their selection). Considering that the AR5 is an ongoing report, water resource managers and scientific experts should examine up-to-date developments when selecting their bounding emissions-related scenarios.

Unlike the simple approach for emissions uncertainty, it is less straightforward to deal with the other uncertainty sources. It is generally important to account for all uncertainty sources (Quintana Seguí et al. 2009), but the question

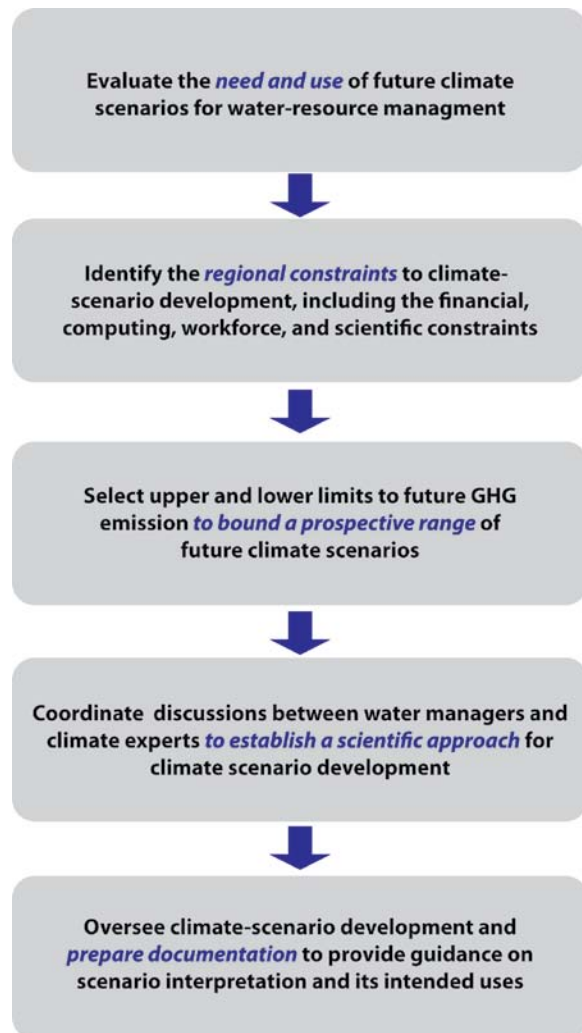


Figure 4. Holistic framework to guide climate scenario development for water resource managers.

of how to account for these uncertainties cannot be separated from other fundamental decisions (e.g., selection of downscaling techniques). These other decisions are themselves controlled by non-scientific constraints to climate scenario development.

The various sources of uncertainty are a primary reason why the options for climate scenario development are not unique. Water resource managers will often have many options in how they account for uncertainties. Unfortunately, there is no established methodology in scientific literature to dictate how extensive uncertainty analyses should be. In fact, the majority of scientific efforts for high-resolution climate scenario development do not fully account for all sources of uncertainty.

Each of the steps in the proposed framework necessarily requires the expertise from the interdisciplinary team formed by water resource managers. Applying this framework with a team can help water managers overcome the shortcomings that are common to many climate scenario development efforts. For example, water resource managers might have a limited background in climate science, while a climate scientist might not fully understand a project's water-related objective and non-scientific constraints. When addressed through improved lines of communication, these shortcomings can strengthen the process and results of climate scenario development. The framework provides a platform that should foster clear and frequent dialogue among team members to share knowledge and optimize efforts. Finally, the framework emphasizes the need to document the entire process of climate scenario development to help water managers answer subsequent questions by decision makers and others.

Discussion and Conclusions

An optimal approach for climate scenario development can only be reached through iterative discussions on scientific and non-scientific constraints, which stem from continuous dialogue between water resource managers and their team of experts. The dialogue should result in the creation of a set of plausible climate scenarios at specific spatial and temporal resolutions that best meet the end-users' needs, given the financial and other non-scientific constraints that limit climate scenario development. To be valuable to end users, a clear description of the assumptions and uncertainties should accompany any set of climate scenarios.

The holistic framework in Figure 4 and the discussions above emphasize that water resource managers should ideally work together with a interdisciplinary team of experts to select appropriate downscaling methods and build a prospective range of scenarios to inform water resource projects. It is also helpful for water resource managers and their teams to understand the uncertainties that are inherent to climate scenario development and how they relate to the different downscaling approaches.

Understanding the uncertainties associated with developing climate scenarios is an important part of the development process. Climate scenario-development teams benefit from this knowledge, because it allows them to make more informed decisions on which model and technique to use to build the most robust and effective range of climate scenarios for water resource assessments.

The challenge of making decisions in the presence of uncertainty is not unique to water resources and climate; policy and management decisions are made every day, even with uncertainties, for a wide range of issues. McMichael et al. (2003) point out that many different criteria exist for decision making on climate-related policy, including the precautionary principle and cost-benefit analysis. These authors emphasize that an understanding of uncertainty and its various sources is essential; otherwise, the developed climate scenarios may be misleading. In the context of water resource management, uncertainty-based analyses allow quantification of uncertainties in key water-related variables (e.g., precipitation and temperature). With this additional information, the potential implications of climate scenario uncertainties for outcomes of concern to water resource managers will be clearer. Ultimately, climate scenarios developed using the holistic framework proposed here will enable water resource managers to make informed decisions about the likely impacts of climate change on water resources.

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